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The System for Precise Measurement of Accelerator Extraction Efficiency†

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Abstract

The extraction efficiency of the Fermi National Accelerator Laboratory synchrotron is determined by measuring the extraction inefficiency with a simple calibrated loss-measuring system. The relative inefficiency subtracted from unity gives a precise measurement of extraction efficiency from measurements made with only nominal precision. An uncertainty of ± 10 percent in the inefficiency measurement allows extraction efficiency of 99 percent to be known with an uncertainty of ± 0.1 percent. The concept also can be used to intercalibrate accelerator internal and external intensity monitors and to indicate the amount of beam that may be lost elsewhere in a large accelerator. The concept, system, and applications are discussed.

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Introduction

The traditional measurement of the extraction efficiency of an accelerator as the ratio of an external-beam intensity measurement to an internal-beam intensity measurement gives imprecise results as extraction efficiency approaches 100 percent. The use of this ratio requires exceedingly accurate intercalibration of the internal and external intensity monitors, as well as high resolution in their readings. Improvements in the extraction system are not distinctly evident and become less discernable as 100 percent extraction efficiency is approached; furthermore, indicated extraction efficiencies greater than 100 percent are not unusual in this situation.

A simple calibrated loss-monitor system[1] is used to measure directly the extraction inefficiency, or losses, at the Fermilab (Fermi National Accelerator Laboratory) main accelerator. The technique allows extraction efficiencies to be precisely determined for both slow and fast extraction. The relatively small inefficiency, measured to a nominal precision and subtracted from unity allows extraction efficiency to be determined with much greater precision than previously possible. Indicated extraction efficiencies greater than unity are precluded. The method also allows accelerator internal and external intensity monitors to be accurately intercalibrated and to indicate if significant amounts of beam are lost anywhere else in the accelerator. A similar concept has been effected for slow extraction at the proton synchrotron for the Joint Institute for Nuclear Research, Dubna, USSR.[2]

Theory

Assume that extraction losses greatly dominate other beam losses during extraction or that this situation can be contrived. Under these conditions, the following equation accounts for all protons, those accelerated, those extracted, and those lost in the extraction system:

$$N_a = N_x + N_{lx}, \qquad (1)$$

where N_a is the number of protons accelerated, N_x is the number of protons extracted, and N_{1x} the number of protons lost in extraction. Dividing both sides of the equation by N_a normalizes the expression, yielding:

$$1 = \frac{N_x}{N_a} + \frac{N_{1x}}{N_a} , \tag{2}$$

$$1 = \frac{N_x}{N_a} + \frac{kXLM}{N_a} , \tag{3}$$

$$1 = \varepsilon + \bar{\varepsilon} , \tag{4}$$

where k is an experimentally determined calibration constant for the loss-monitor system, XLM is the reading of the extraction loss-monitor system, $\varepsilon \equiv \frac{N_x}{N_a}$, the traditional extraction efficiency, and $\bar{\varepsilon} \equiv \frac{N_{1x}}{N_a}$, the extraction inefficiency.

Eqs. (2), (3), and (4) are straight lines between one intercept where the extraction efficiency is unity (losses $\equiv 0$) and the other intercept where extraction efficiency is zero (all beam is lost) as indicated in Fig. 1. The constant k is chosen to normalize the ordinate when the following experiment is done. The extraction channel is purposely detuned (at reduced beam intensity) so that all the accelerated beam is lost in the channel and no beam survives extraction. This situation satisfies the $\bar{\varepsilon} = 1$, $\varepsilon = 0$ condition of the ordinate in Fig. 1. The corresponding reading of the extraction loss monitor (XLM) and the accelerated protons (N_a) are recorded. N_x must of course equal zero. The value of k is calculated to satisfy the expression:

$$\frac{k\ XLM}{N_a} = 1, \tag{5}$$

which is simply Eq. (3) with $N_x = 0$. This procedure calibrates the extraction loss-monitor system.

The extraction system may now be retuned to the normal operating condition. The operating efficiency at that point is determined by first measuring the inefficiency $\bar{\varepsilon}$ with the calibrated loss-monitor system and then finding the efficiency ε from:

$$\varepsilon = 1 - \bar{\varepsilon} \, . \tag{6}$$

The precision with which extraction efficiency can be determined by this method approaches perfection as accelerator extraction efficiency approaches unity as long as any error in the calibration of the extraction loss monitor is finite.

An alternative approach to determining k is to plot a series of points in the graph of Fig. 1 as extraction efficiency is varied over a large range, which does not have to include the $\varepsilon = 0$ (all beam lost) nor the $\varepsilon = 1$ (no beam lost) points. A straight line should result from this plot. Extrapolation of this line to the ordinate yields k. When using this alternative calibration method, it is important that the external intensity monitor be located where it is free from measurement error derived from the effects of extraction losses.

The Fermilab Accelerator Extraction System

As a prelude to discussing the extraction loss-monitor system, the general configuration of the Fermilab main accelerator extraction system will be discussed. For a description of the extraction system, see Dr. R. R. Wilson's article in Scientific American.[3]

The first elements in the extraction chain are two 10-foot long electrostatic deflectors which have septa consisting of vertical 0.002-in. diameter tungsten wires spaced 0.05 in. apart. The 70 kV electric field in these elements impart a horizontal deflection of 0.14 mrad to that portion of the beam entering the field region, directing this beam into the magnetic channel of the extraction magnet. One-hundred feet downstream from the electrostatic septa are two 10-foot long Lambertson magnets with 0.050-in. thick septa. The magnetic field deflects the beam downward 3 mrad towards the next element in the channel. Thirty-five feet downstream from the magnetic septa, the beam enters a vacuum pipe separate from that of the accelerator and passes through a chain of three "C" magnets and seven "H" magnets each 10-ft. long. Emerging from the last of these magnets, the extracted proton beam clears the outside edge of the main-ring magnets and is a true external beam 275 ft after entering the electrostatic septa.

The main ring is four miles in circumference and the extraction system comprises a relatively small segment of the accelerator.

The Extraction Loss Monitoring System

The extraction loss detector is a long ionization chamber of RG319 A/U, which is a commercially available[4] spiral-insulated coaxial cable similar to that used at the Stanford Linear Accelerator.[5] This 1-5/8-in. diameter cable is mounted on the ceiling of the enclosure about 15 ft. from the accelerator and runs generally parallel to the extraction system. The cable starts at the upstream end of the electrostatic septa and terminates 400 ft. downstream, which is 125 ft. downstream of the last magnet in the extraction chain.

Displaced 15 ft. from the extraction system, the loss detector is not particularly sensitive to any single loss point and is located where the radiation flux density is relatively low to provide linear performance for fast, short spills as well as for slow, long spills. The continuity of the detector provides spatial integration of all the losses in the extraction system and the length provides a high sensitivity to the total losses. Gas flow at $\sim$ 0.02 L/min of 90 percent Ar and 10 percent CH_4 is maintained through the detector.

The jacketed shield of the coaxial loss detector is biased at 1.5 kV. The signal obtained from the center conductor is connected to a gated integrator having a 5 μf integrating capacitor. Following the end of the extraction process, the integrated charge is digitized for display in the main control room. The gating is used to sensitize the circuit during the extraction time only. Complementary gating is optionally available to measure injection or other losses.

Supplementing the long extraction loss monitor is a series of small independent loss monitors located directly on each extraction element. These uncalibrated monitors are highly sensitive to local loss points and are used to indicate specific loss locations and to align extraction elements precisely.

Results of Calibration Experiment

Residual-activity measurements confirm that beam losses are almost totally contained in the extraction elements. Occassionally, some of the accelerated beam may be directed into an internal beam dump halfway around the circumference of the accelerat A beam-abort system is routinely triggered at a time near the end o ..e extraction process, and any beam remaining in the accelerator is deposited in this internal dump. Except for this dump, the remainder of the accelerator is relatively free of residual activity. Consequently, as long as no beam is aborted, extraction losses greatly dominate other losses during extraction, a condition that complies with the assumption stated in the theory above.

Data for the calibration of the extraction loss monitor were collected as the extraction system was tuned over extraction efficiencies ranging from about 8 per cent to 90 per cent. (The Fermilab main accelerator now operates routinely near 99 per cent efficiency.) At each of several levels of efficiency, readings were recorded of the extraction loss monitor (XLM), the external intensity monitor (XSEM), and the accelerator internal intensity monitor (MRI).

Experiments have shown that the external intensity monitor is situated in a location free from significant measurement error derived from the effects of extraction losses.

Figure 2 is a plot of XLM/MRI (proportional to $\bar{\varepsilon}$) as a function of XSEM/MRI (proportional to ε). A reasonably small scattering of points allow a straight line to be fitted without difficulty. (Disregard for the moment the circled points, which are discussed later.) Extrapolation of the line to zero extraction efficiency, $\bar{\varepsilon} = 1$, shows that the loss- monitor calibration is:

$$k \approx \frac{1}{19} \frac{\text{XLM}}{\text{MRI}} . \qquad (7)$$

The extraction efficiency in terms of Eq. (6) for the calibrated loss monitor is then:

$$\varepsilon \approx 1 - 0.05 \frac{XLM}{MRI} . \tag{8}$$

As a matter of practice, a variation of this equation is used to measure extraction efficiency. This practice .lts from the sequence in which accelerator intensities must be measured and recorded. The internal intensity (MRI) is measured and recorded immediately preceding the start of the extraction process. The recorded value represents the number of particles stored in the accelerator. During extraction, these particles leave the accelerator in a controlled fashion over a period of time up to a second. The external intensity monitoring system must integrate the signal resulting from the particles traversing the device so that at the end of the extraction process, the time integral of the signal represents the particles extracted. If, during extraction, particles are lost elsewhere around the accelerator (as when protons are aborted into the internal dump) and do not participate in the extraction process, the extraction efficiency determined by Eq. (8) is erroneously high. Consider the extreme case where all the accelerator beam is aborted after MRI is recorded but before extraction starts. MRI will be a large number, XLM will be approximately zero, and extraction efficiency as indicated by Eq. (8) will be nearly 100 percent even though no beam is in fact extracted. A way to avoid this error is to substitute for MRI in Eq. (8) the equality:

$$MRI = XSEM + kXLM, \tag{9}$$

which is Eq. (1) with the symbols replaced by measured values. [Eq. (9) assumes correct intercalibration of the MRI and the XSEM intensity monitors. This intercalibration is discussed below.] Substituting Eq. (9) into Eq. (8), we find a general expression to be used for measuring accelerator extraction efficiency as follows:

$$\varepsilon = 1 - \frac{kXLM}{XSEM + kXLM} \tag{10}$$

$$\varepsilon \approx 1 - \frac{kXLM}{XSEM} \qquad kXLM << XSEM \text{ i.e. relatively small extraction losses.} \tag{11}$$

The use of Eqs. (10) or (11) precludes erroneous enhancement of extraction efficiency if protons are lost elsewhere in the accelerator after the accelerator intensity has been recorded. Because efficiency is defined in terms of only those protons entering the extraction channel, these equations also allow correct efficiency measurements of an accelerator using internal targets that intercept part of the beam. It is explained below how this concept is extendable to measure the number of particles targeted or lost elsewhere in the accelerator.

Intercalibration of Intensity Monitors

At 100 percent extraction efficiency, both internal and external intensity monitors would sense exactly the same number of protons and therefore should indicate the same, if properly intercalibrated. Extrapolation of the line in Fig. 2 to the abscissa where extraction efficiency would equal unity and the losses would equal zero, shows the XSEM/MRI ratio to be about 1.05. This result suggests that the external intensity monitor is registering about five per cent higher than the internal intensity monitor. Of course, which, if either, is absolutely correct is not resolved by this technique, but either one may be brought into agreement with the other. Precise intercalibration allows the capability discussed next.

Determination of the Number of Protons Lost Other Than in the Extraction System

The circled points in Fig. 2 will now be considered. On two accelerator pulses, some of the accelerated beam was evidently diverted into the accelerator abort dump or lost elsewhere after the accelerator intensity was recorded. As discussed earlier, this condition gives an erroneously low XLM/MRI ratio and a corresponding low XSEM/MRI ratio. Protons aborted are recorded as part of MRI but do not participate in extraction either to produce extracted beam or extraction losses. The relative number of protons so dumped or otherwise lost can be determined by noting the distance the circled points lie to the left of the calibration line in Fig. 2. On the other hand, given a properly intercalibrated internal intensity, external intensity, and extraction loss monitor, the number of protons so lost can be quantitatively determined. Eq. (1) can be expanded as follows:

$$N_{le} = N_a - N_x - N_{lx} , \tag{12}$$

where N_{le} is the number of protons lost elsewhere. Every quantity on the right of Eq. (12) is measurable and N_{le} can be calculated to the precision of the measurements. Greater accuracy could be achieved if a separate calibrated loss monitor spanned the remainder of the accelerator so that N_{le} could be measured directly, but where the accelerator is four miles in circumference, the use of Eq. (12) proves attractive and useful.

An Alternative Form of Extraction Loss-Monitor System

A single long-loss monitor as described above is simple to implement and works rather well. Other arrangements may be required or desired to implement this concept of measuring extraction efficiency. In particular, consider replacing the single long-loss monitor with a number of short individual loss monitors each having an individually adjustable gain (weight) so that

$$\text{SUM XLOSS} = \sum_{i=1}^{n} K_i L_i , \tag{13}$$

where L_i are the individual loss-monitor outputs, K_i are the individual loss-monitor gains, and n is the number of loss monitors. The individual K_i (weighting coefficient) can be adjusted to make the points as in Fig. 1 fall on a straight line to greater precision. Such a system was implemented for the AGS at Brookhaven National Laboratory, where n = 3 gave satisfactory results.[6]

Error

One estimate of the uncertainty in the extraction loss monitor system can be achieved by noting the scatter of points in the graph c^ ^ig. 1. One dashed line is drawn through the uppermost range of the data poir , and another line is drawn through the lowermost. Extrapolation of these lines to the ordinate indicates an upper error range for the uncertainty in the calibration constant k. For the data shown here, the error range as indicated is approximately ± 2 units out of 19 or roughly ten per cent. Since $\varepsilon = 1 - k$ XLM/MRI, the magnitude of this error means 90% extraction efficiency is known to ± 1 per cent and 99 percent extraction efficiency is known to ± 0.1 per cent.

Alternatively, the error can be estimated by noting the scatter of the XLM/MRI ratio when all the beam is lost in the extraction channel. Such a plot would yield a cluster of points along the ordinate, from which a mean and a standard deviation could be determined. The scatter of these points would be an indication of the susceptivity of the loss detector to the loss location, and as such would more fully represent the imperfections of the detector system than the method above since error contributions from the external intensity monitor are eliminated. Furthermore, small amounts of beam lost elsewhere in the accelerator have a diminished effect on the calibration when losses are large.

Discussion

This technique allows accelerator extraction efficiency to be measured with greater precision than any other known method; therefore, no direct verification of accuracy has been achieved, but indirect evidence supports the method. Improvements in the extraction system have brought expected increases in indicated extraction efficiency. Optimum alignment of the extraction electrostatic septa is also distinguished by a distinct minimum in the inefficiency as measured with the extraction loss monitor.

Other supporting evidence is obtained from records of residual activity in the extraction system compared with records of accelerated-beam intensity and accompanying extraction inefficiency. Fig. 3 shows a plot of accelerator beam intensity, accelerator inefficiency, and the product of these two values (the number of protons lost) which is proportional to induced activity. Independent residual-activity measurements support the decrease in activity that occurred through this period in spite of the increasing numbers of accelerated and extracted protons.

The extraction loss-monitor system is routinely operated with an alarm that sounds whenever the number of protons lost in the extraction system exceeds a specified number. Another alarm is used to indicate when the number of protons lost elsewhere in the accelerator [as given by Eq. (12)] exceeds a given number. This facility has helped to maintain induced activity at reasonably low levels.

Conclusion

The extraction loss-monitor concept has been especially useful for measuring small changes in extraction efficiency. The system has been invaluable in understanding and improving the accelerator extraction system for both fast and slow spill. As a result, induced activity in the accelerator has been minimized, but regardless of whether the loss monitor is calibrated the ratio of the loss detector reading to the extracted beam intensity is a useful ratio to monitor and to minimize. Relative improvements in the extraction efficiency are distinctly discernable and quite evident.

This loss monitor system is simple, economical, and reliable. It has operated for over two years without attention. The concept has been extended to other applications such as measuring and optimizing efficiencies of external beam-splitting stations and assessing collimator transmission efficiencies.

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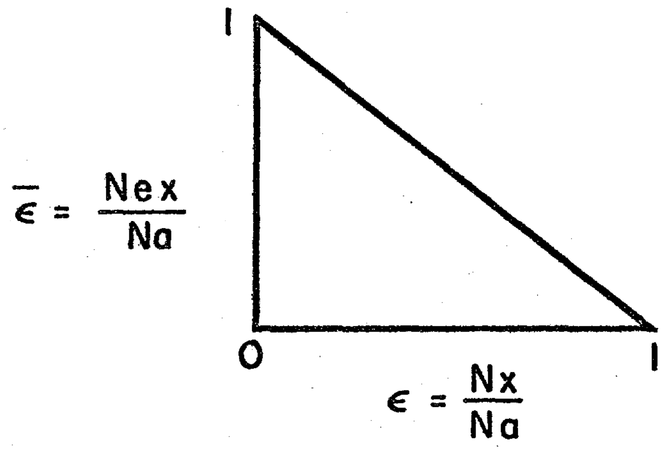

Fig. 1 Inefficiency as a Function of Efficiency.

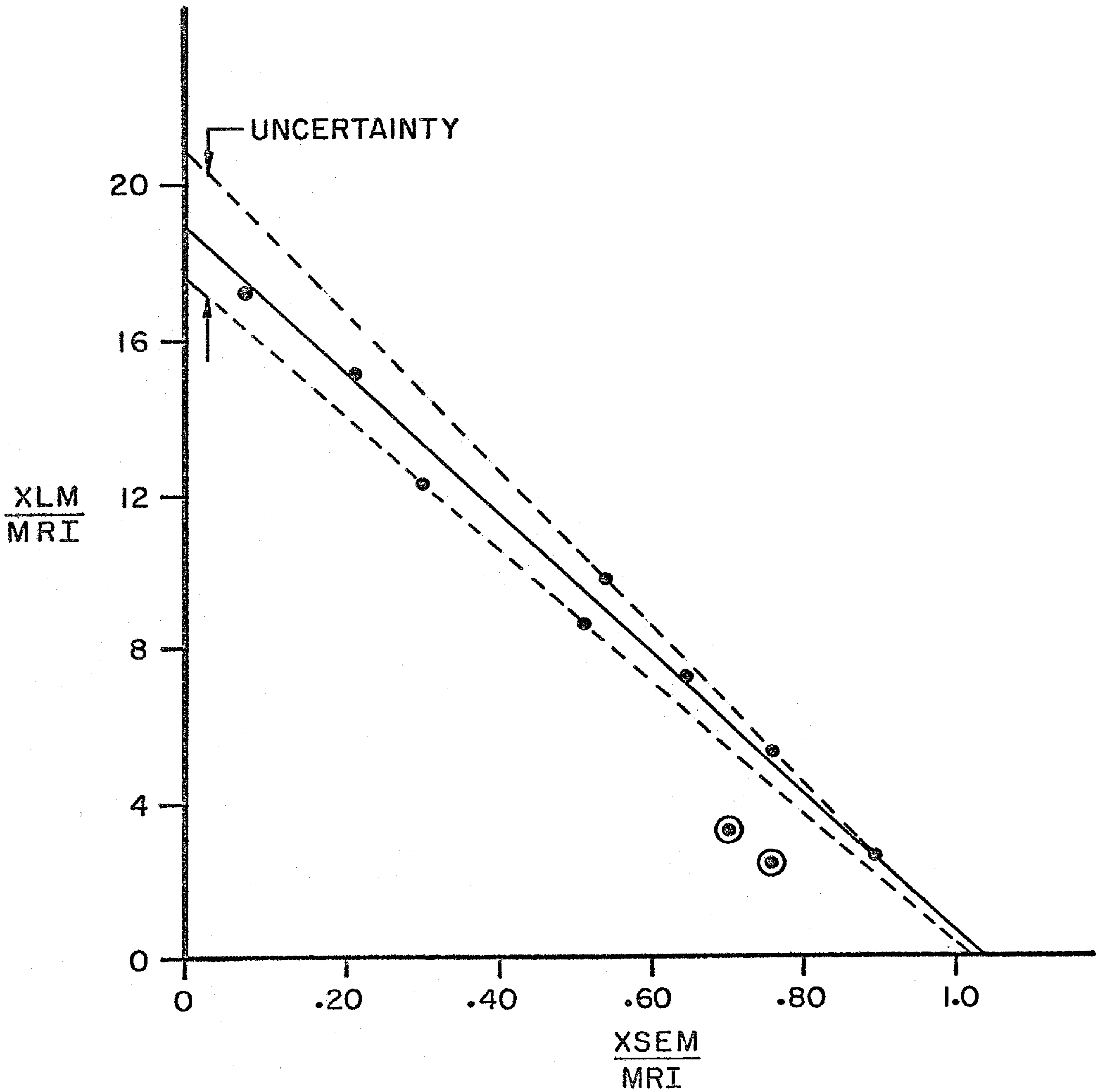

Fig. 2 Extraction Loss Monitor per Main Ring Intensity (XLM/MRI) as a Function of External Beam Intensity per Main Ring Intensity (XSEM/MRI).

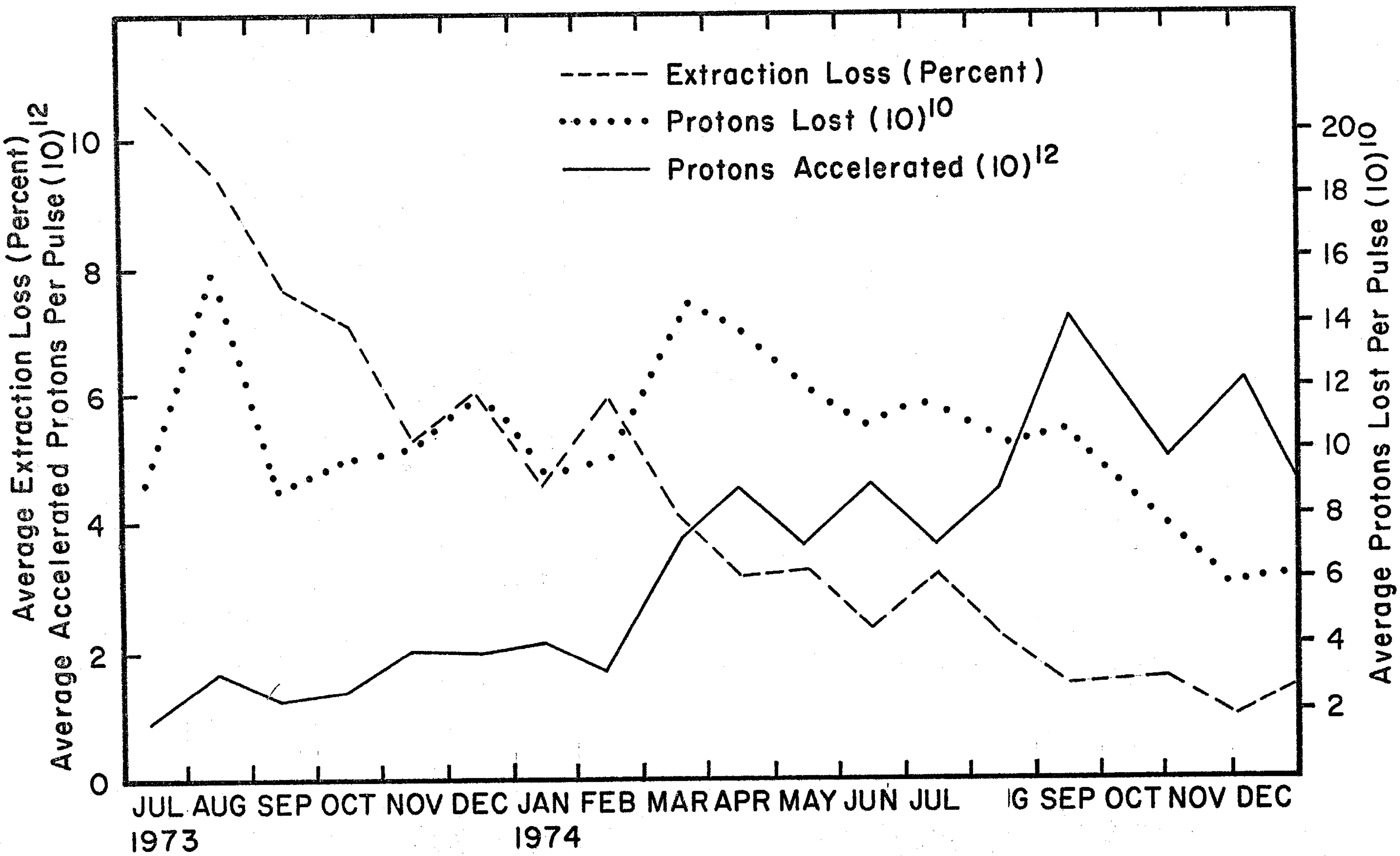

Fig. 3 History of Average Number of Protons Accelerated per Pulse, Average Extraction Inefficiency, and Average Number of Protons Lost per Pulse.

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